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METHODOLOGICAL NOTES

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Laser beam in a soap film

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Contents

Abstract. **A laser beam introduced into a simple soap film unexpectedly breaks out into thin (micron-thick) branching channels which keep unspread (without divergence) sometimes for as long as tens of centimeters as they go along the film. The physical interpretation and possible applications of the phenomenon are discussed in this paper.**

1. Introduction

Soap films and bubbles have been attracting people's attention for many centuries [1, 2]. Still, they keep presenting new surprises for researchers and manifest an unending variety of fascinating features and marvels. In recent papers [3 – 6], a strange behavior of a laser light in ordinary soap films was reported. This counter-intuitive behavior is totally different from the usual scattering of a beam in the bulk of the same soap solution. It can be observed in a planar or bent free-standing film made of the water solution of any ordinary soap, of almost any concentration, or of any chemically pure surface-active agent (surfactant) that can form in the air free-standing films with a diameter of 5 – 15 cm and a thickness of 10 nm – 10 μm. In such a film, an introduced visible or infrared laser beam breaks, immediately after the focal point, into thin (micron-size) bright channels, which propagate further without characteristic diffraction divergence and no noticeable decrease in intensity (see Fig. 1), sometimes at distances of tens of centimeters. These light tracks (or 'whiskers', as we will call them because of their sharp ends) can be easily seen by the naked eye even in most transparent solutions. They permanently change their ways dozens of times a second, keep breaking and branching, like lightning streamers, and easily intersect with each other (see the video attached to Ref. [4]). Their shape and thickness are almost independent of the temperature (in the range 0 – 30 °C) and of the parameters of the laser (its wavelength, polarization, and intensity). In particular, in our experiment the intensity was varied by nine orders of magnitude, from 10 μW to 2 W in the continuous-wave (CW) regime and up to 10 kW in a single pulse of 10 ns duration. We observed similar whiskers in a film made of the surfactant 'Triton X-405' solution in kerosene.

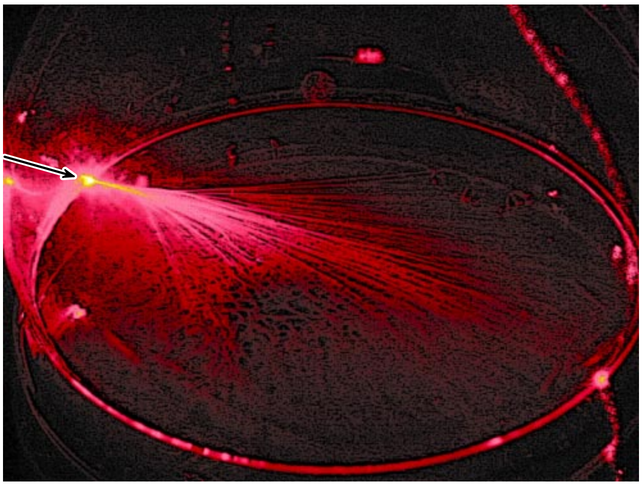

Figure 1. Tracks observed from a beam of a CW He – Ne laser (with intensity 5 mW and wavelength 632.8 nm) focused by a lens with $F = 10$ cm onto the rim of a convex soap film with thickness 5 – 10 μm and diameter 85 mm.

It is interesting to discuss the physics of this phenomenon, which is extremely unusual and attractive but easy to observe without professional equipment. In addition, this phenomenon is also interesting from the practical viewpoint. Indeed, a film with rapidly changing and branching narrow channels can be considered as a real model of a high-power self-organized optical computer, which provides permanent sensitive control of the film dynamics and determines the time and place of the next 'route switching' for its narrow tracks [5].

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The refractive index for the tracks can be estimated from the change of the track angle with respect to the initial direction of the exciting laser beam. For films of various thicknesses, its value is between 1 and 1.28 [4], being close to unity in the thinnest films. Since all these values considerably differ from the refractive index of the soap solution (1.33 – 1.45), one can conclude that the radiation in a narrow track propagates, like surface electromagnetic waves, both through the film and through the air. It should be noted that no earlier studies in any materials ever revealed the breaking of a weak laser beam into such narrow whiskers; this phenomenon is caused by the structural features and nonlinear properties of ordinary soap films.

2. Laser tracks in liquid soap films

Soap films have molecular-layer structure [1, 2]. Their inner layer, whose thickness is usually less than 10 μm, is always homogeneous; on both its sides there are continuous monomolecular layers of soap molecules oriented normally to the film and densely packed into a two-dimensional crystalline layer, similar to a Langmuir – Blodgett two-dimensional crystal. As the solution flows down, the film thickness (~ 10 μm) is gradually reduced by three orders of magnitude. At this stage, interference fringes become visible on the film in reflected light, and one can use their number and color to determine the film thickness [4]. When the thickness becomes smaller than approximately ten times less than the wavelength of visible light, the film looks silver in reflected light, then colorless-gray, and then black, which means that it reflects almost no light. The solution keeps flowing down, the thickness of the black film reduces another ten times, and finally, both its outer layers of molecules come together and form the so-called truly black (Newtonian) film. This film consists of only two crystalline layers of molecules with a total thickness of 5 nm, which is 100 times less than the wavelength of visible light.

In our series of experiments, a slightly concave horizontal film was prepared in a closed plastic bottle (with volume 0.5 l and diameter 65 mm) on the level of the bottle waist, the lifetime of such a film being typically ten to twenty hours. By means of a lens with $F = 10$ cm, a laser beam was focused into the rim (the Plateau border) of the film through the transparent bottle wall or onto the surface of the film through the air. The beam waist diameter was about 30 μm. During the experiments, it was noticed that concave films have considerably weaker drain flows, better optical homogeneity, and slower track switching rate compared to convex films. The tracks were observed at various angles (Fig. 2) and their photographs were taken through the bottle wall. In order to increase their brightness, a slightly opaque (scattering) soap solution was used.

With a laser beam focused at a grazing angle (less than 10°) into the center of a film of thickness 0.3 – 0.6 μm (which corresponds to several interference fringes in the reflected light), or onto a spherical soap bubble with the radius 1 – 5 cm and the same thickness, one can sometimes obtain whiskers in the shape of a ring or another closed figure. However, the whiskers in the same film can be straight, i.e., propagate along straight lines crossing colored inhomogeneities clearly seen in reflected light (Fig. 3) [6]. Sometimes, several whiskers are created at the focal point, and their further crossings manifest no interaction between them, as if different whiskers did not see each other (Figs 4, 5).

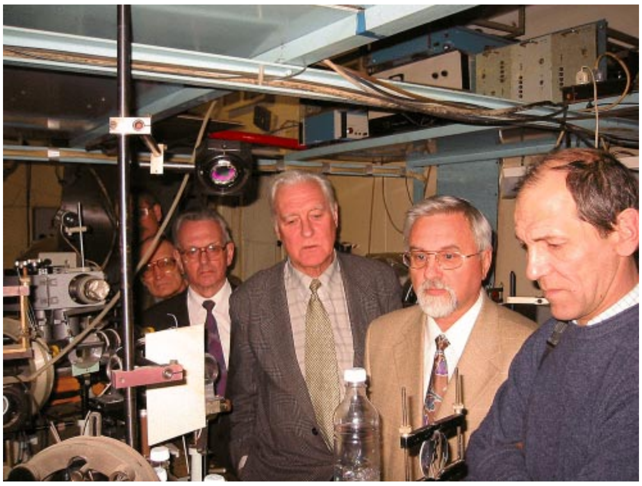

Figure 2. Observation of laser tracks in a soap film at various angles.

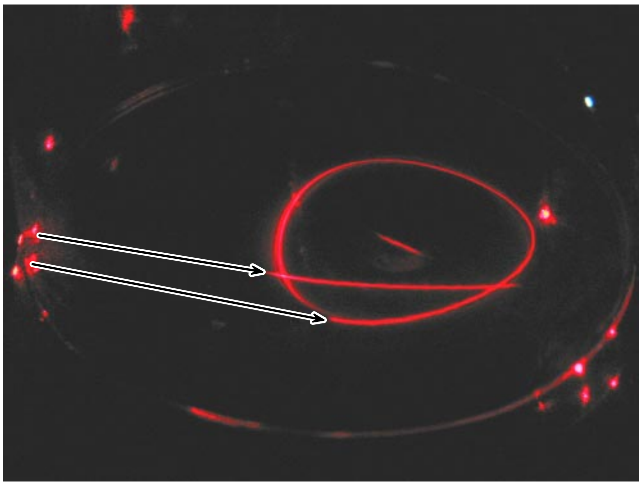

Figure 3. A closed non-circular track and a straight track on a concave film. Both input beams simultaneously focused onto the film from above are shown by arrows.

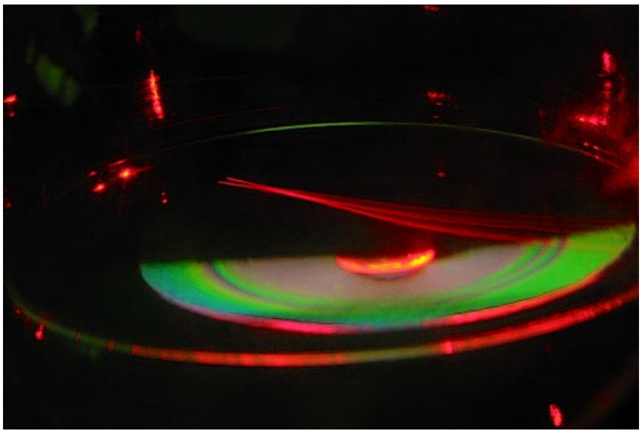

Figure 4. Bunches of straight whiskers on a film excited by two lasers. Intersecting tracks do not influence each other.

As the solution flows down, the concave film gets thinner near the wall and becomes black on the edge (which indicates that the thickness has become less than 50 nm). In its center, there remains a circle of thicker film gradually reducing in size and surrounded by a distinct border. If a laser beam is focused

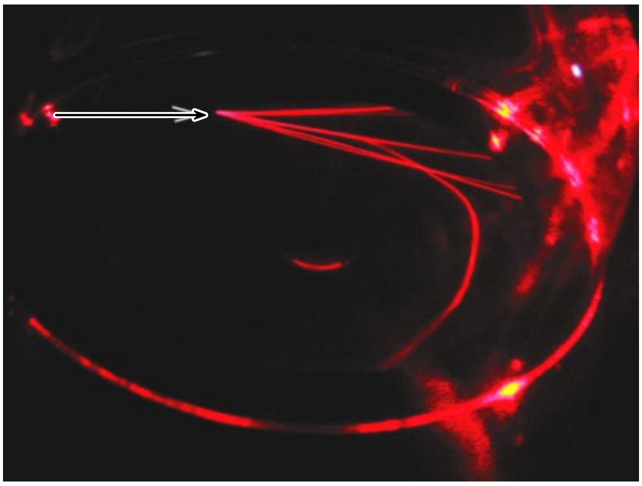

Figure 5. Whisker bunches on a film excited by a single laser. Intersecting tracks do not influence each other.

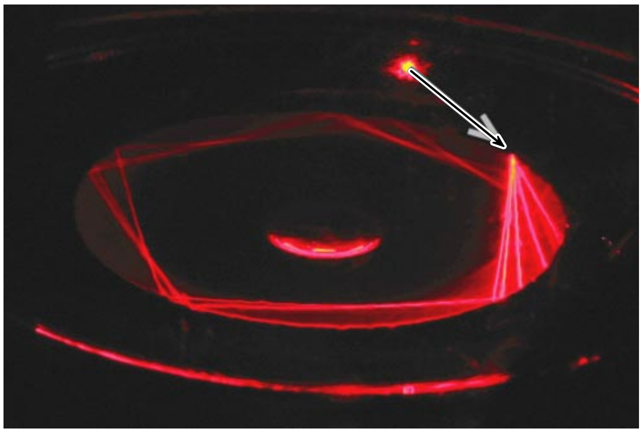

Figure 6. Laser tracks following the chords of a circular film, with nearly total reflection from the film border. Tracks with small refraction relative to the initial beam direction (shown by the arrow) do not reflect from the border.

through the air onto this border between the thinner (less than 50 nm thick) and the thicker (more than 100 nm thick) parts of the film, the resulting whiskers look like those shown in Figs 5–8. No whiskers are created if the beam is focused outside this border. If the beam is focused into the circular border along its tangent, from one to seven slightly moving tracks usually emerge at the focal point (see Figs 5, 6) and travel along clearly defined directions. The distance between different tracks exceeds the visible track thickness dozens or hundreds times, and hence each track can be considered as a separate optical object. If the inner circular film is pre-black (i.e., only slightly thicker than a black film but still having a silver-gray color), the most strongly refracted track follows straight chords of its rim (see Figs 7, 8). It exhibits almost total internal reflection at the border, covers a distance of more than 10 cm without visible divergence (even becoming thinner), and forms a nearly regular pentagon. To provide this nearly total reflection from the circular border between the black film and the thick one, the relative refractive index for the track should be close to 1.05.

Not only the shape, but also the behavior of the whiskers, which change their direction without any evident reason, is quite surprising. If we assume that the whiskers feel the inhomogeneities of the film and toss about in its flows, then why do they remain straight in the colored inhomogeneities distinctly visible in reflected light (see Fig. 3) [6]? Why are several whiskers sometimes born at a single focal point? Why are the ends of the whiskers sharp (Fig. 9)? Why do whiskers intersect (see Figs 4, 5) without any interaction, without 'seeing' each other?

Our observations revealed another strange feature, which has never before been reported in optics. This is the unusual behavior of the track that is closest to the center of the circle. As one can see in Figs 7, 10, along its whole path it consists of

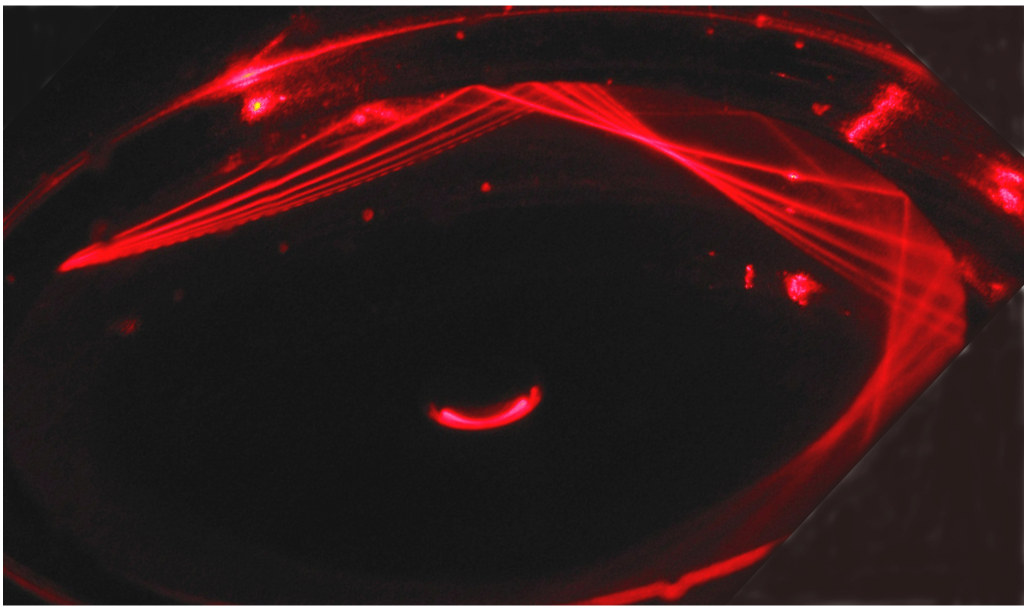

Figure 7. Laser tracks forming a pentagon with nearly total reflections from the border of a circular film.

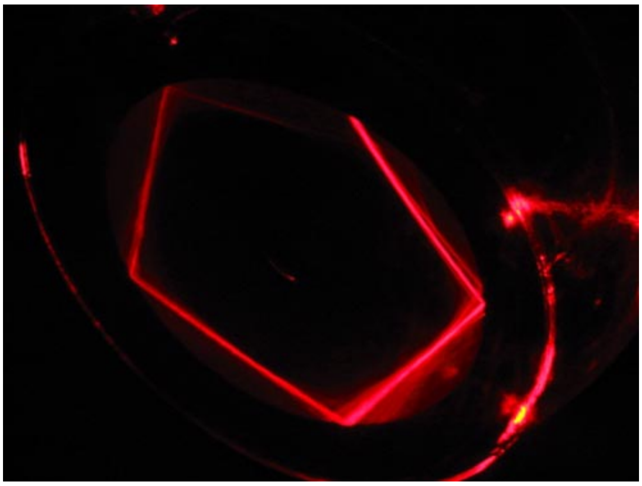

Figure 8. A laser track going along the chords of a round film with no noticeable divergence and with nearly total reflection from the border.

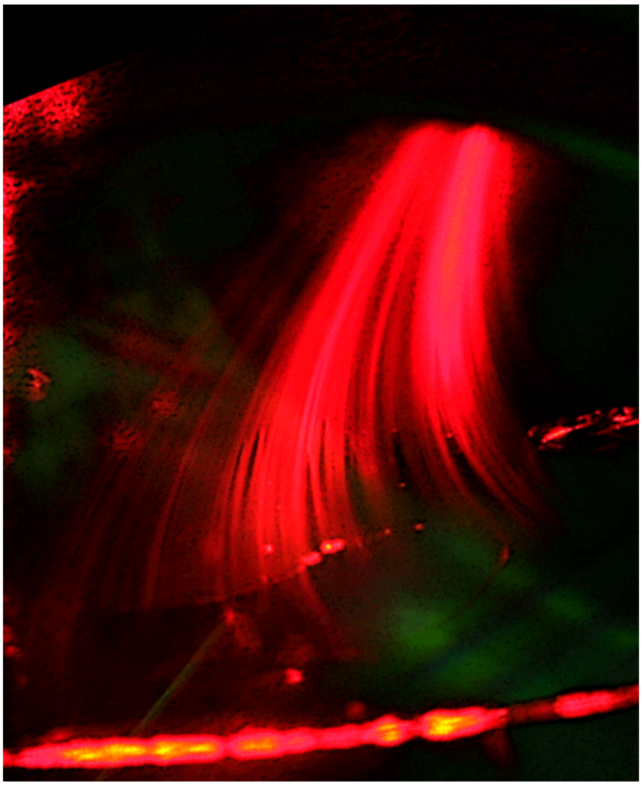

Figure 9. Ends of the whiskers in a film with a length of 10 cm and a thickness of about 100 nm [2].

alternating dark and bright dashes with lengths varying from 0.5 to 2 mm, depending on the experiment. This means that the track emits light somewhat discontinuously.

3. Laser tracks in liquid and rigid soap films under a microscope

It was interesting to have a more detailed, magnified look at the tracks. We wanted to understand the difference between the whiskers that propagated along their own directions, with their own swinging amplitudes, from the same focal zone and to find out what determined their number and refraction angles.

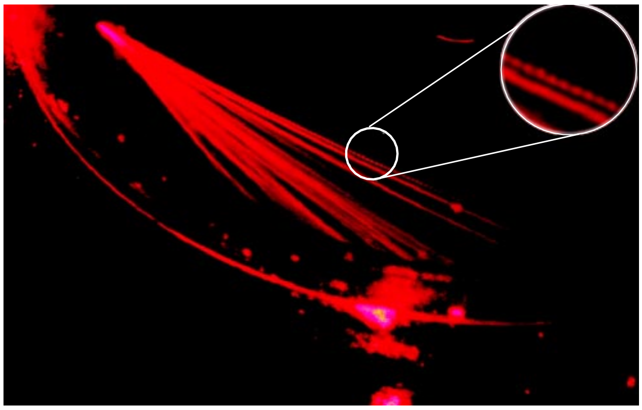

Figure 10. The dashed structure of the track that has the largest refraction relatively to the incident laser beam direction. Along its whole path, the track consists of alternating bright and dark dashes with lengths varying, depending on the experiment, from 0.5 to 2 mm.

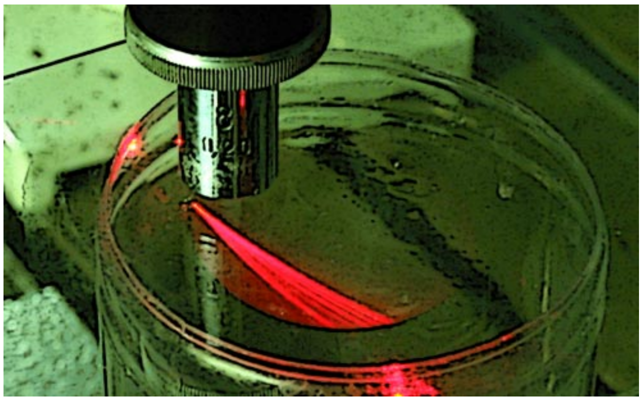

Figure 11. The setup for observing laser whiskers in a soap film under a microscope.

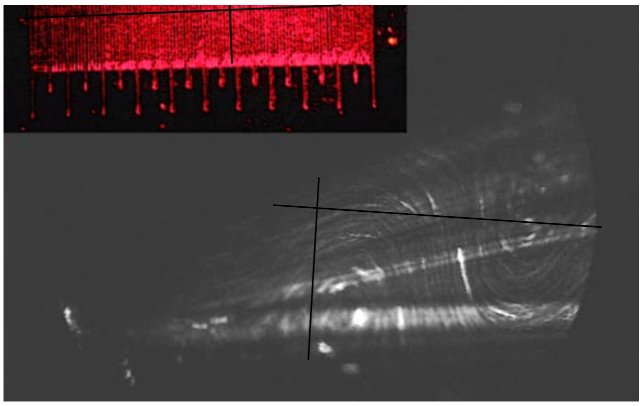

Figure 12. Typical shape of a bunch of whiskers coming from the border of a black film. The whiskers, with a total thickness of 30 – 50 μm, consist of thinner threads whose thickness is 5 – 10 μm. To demonstrate the scale, 1 mm with small divisions of 10 μm is shown in the top part of the figure.

The setup for observing soap films with whiskers under a microscope is shown in Fig. 11. The microscope had approximately a hundred-fold magnification. A typical shape of the bundle of whiskers coming from the border of the black film is shown in Figs 12 – 14a. The whiskers, whose total width is about 30 μm, have thinner threads of about 5 –

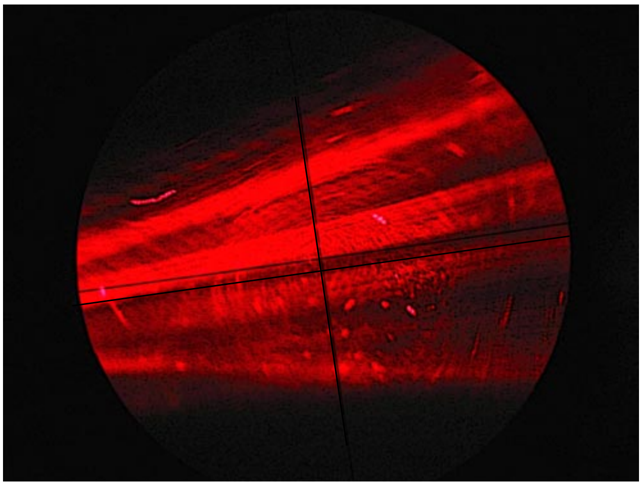

Figure 13. Laser tracks on a concave soap film. The tracks are distorted at the inhomogeneities formed by large dust particles.

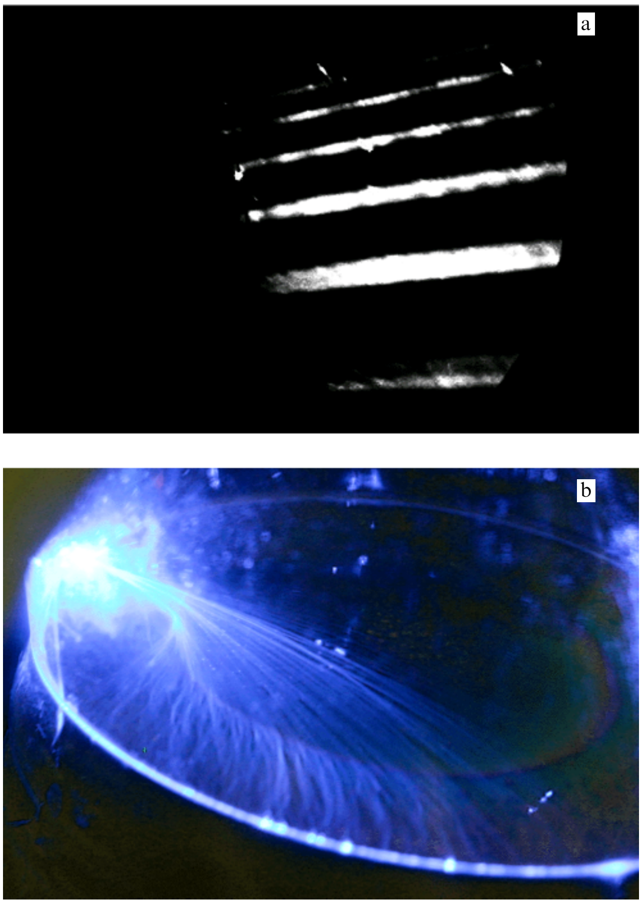

Figure 14. Track bunches on a concave soap film: (a) tracks emerging from the focal zone of a single laser beam and differing by the dash length; (b) tracks excited by a laser with a pulse duration 70 fs, repetition rate 85 MHz, wavelength 475 nm, and average power 1 – 10 μW.

10 μm width. Due to diffraction, a thread of width 5 μm should have a divergence (λ/D) of about ten degrees, i.e., light in such a thread would spread to a tenth of the passed way, i.e., to about 100 μm after passing a millimeter. However, one can see from the figures that the threads have no divergence of this kind.

As we expected, the microscope also revealed dashes in other tracks emerging from the same focal zone (Fig. 14a). According to the figures, the angles between neighboring tracks increase. For tracks emerging from the same focal zone at various angles, the dash lengths differ 1.5 – 5 times. The smaller the dashes, the less the refraction angle for the track (the less the refractive index) and the higher the mobility of the whisker. The laser tracks are clearly seen to be angularly separated and spatially quantized. Sometimes one can see [6] that they emerge from close but still different points of the focal zone.

Under optimal alignment, only about 10% of the pump intensity enters the film. The time of track formation is less than 10 ns, as we have found earlier [5]. The whiskers on the film were clearly seen under illumination by the green (532 nm) pulsed light with a pulse duration of 10 ns. The wavelength of the light from the whiskers coincides, up to 0.001 nm, with the wavelength of the input laser beam (the experiments were carried out using a Fabry – Perot interferometer with a base of 3 cm). Such whiskers were also observed using an input laser with a pulse duration of 70 fs and repetition rate of 85 MHz operating at wavelengths 475 and 950 nm and having an average power of 1 – 150 μW (Fig. 14b).

In the course of investigations, we were able to fulfill our plan [4] to conduct experiments with a hard polymer soap film and to look at immobile whiskers. Recently, Jackie Lin, a chemist from Taiwan, invented a solution for making rigid soap films and bubbles, which remain transparent in the air but become so hard in a few seconds that you can hold them in your hands [7]. The chemical composition and formula of his solution is kept top secret and even unpatented but the solutions are sold in toy shops, and we used them for our experiments.

Before such a film hardens, the whiskers excited in its liquid form keep moving, as in any soap film. In a rigid film, the whiskers do not move and can be studied by changing the laser beam position and orientation. The dry submicron colored film is very strong and elastic (it withstands an expanding force of more than 1 g cm^{-1}). It can be kept in the air for months with very little change, can be stretched, heated up to temperatures of more than 100 °C, cut in pieces, and put on glass. This rigid film with a fixed interference pattern in reflected light is shown in Fig. 15. Darker areas correspond to a thickness of about 100 nm.

By changing the direction of laser whiskers in rigid films, we made sure that the tracks are not permanent light channels

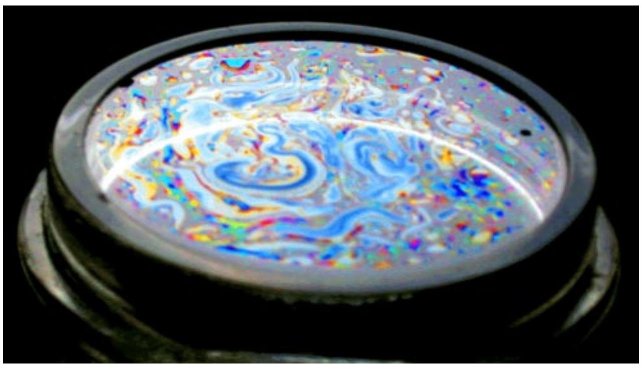

Figure 15. Rigid, dry, and transparent soap film with the diameter 65 mm manifesting a fixed interference pattern in reflected light.

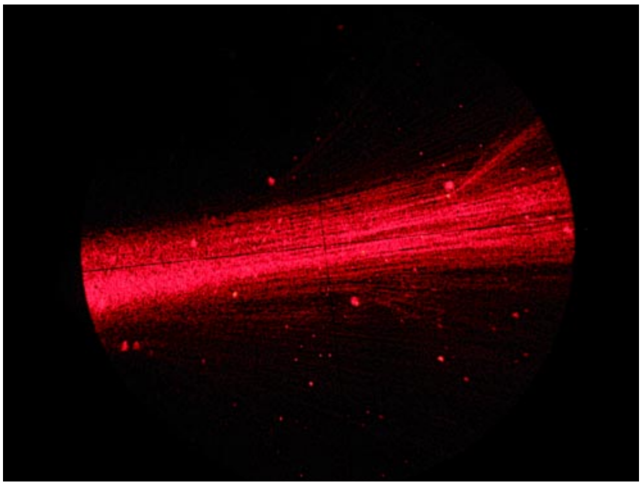

Figure 16. Whiskers with threads in a rigid soap film under the microscope, with distortions near large dust particles.

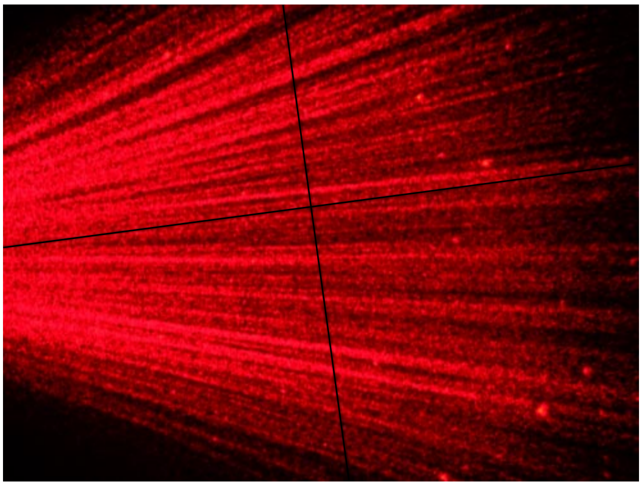

Figure 17. Whiskers with threads in a rigid soap film under the microscope.

or fixed inhomogeneities of the film. Indeed, for a given part of the film their directions depend on the angle of incidence of the laser beam (Figs 16, 17). For dry films, we saw no dashes on the whiskers, probably because of the inhomogeneities. Similarly to the case of liquid films [3 – 5], whiskers disappeared when the film was put in contact with a glass substrate or placed in oil or liquid fluorocarbon. Nor were they observed in thick (noncolored, with a thickness larger than 10 μm) dry films.

4. Explanation of some effects by considering the tracks as laser series-fed rod antennas. Possible applications of the tracks

Summarizing the obtained results, we return to our basic question: what mechanism of whiskers formation could explain their strange behavior? Let us briefly recall the properties of the tracks [3 – 6].

(1) The whiskers are observed in *free-standing* rigid or liquid soap films of thickness less than 10 μm, with a focused laser beam of any wavelength between 440 nm and 1 μm, its intensity varying from 10 μW to 10 kW. Under the same conditions of laser excitation, no whiskers are observed in the bulk or on the surface of a soap solution. Nor do they appear in thin soap films deposited on mirrors or surfaces of mercury or dielectrics (mica or polyethylene), or in thin (3 – 5 μm) solid films of mica, polyethylene, or Teflon.

(2) The whiskers are narrow and have sharp ends; their divergence is less than the diffraction one. They toss about in the liquid film, keep branching, split into new tracks, and can travel to distances of tens of centimeters.

(3) At a single point, there usually emerge from one to seven whiskers (sometimes up to twenty, as in Fig. 1), which further exist as separate optical objects.

(4) The refractive index for the whiskers in the film (1 – 1.28) is less than the refractive index for the solution and can be different for different whiskers in the same film.

(5) The whiskers intersect without any visible interaction (as in Figs 4, 5).

(6) Upon exiting from the film into the air or the solution, the whiskers have the usual diffraction divergence.

(7) In the film, the whiskers change their directions near large dust particles but are unaffected by small particles on their way. Their shape has almost no dependence on the power or wavelength of the laser, the sort or concentration of the soap, the temperature, or the film thickness.

(8) In films made of opaque solutions, which have many inhomogeneities and where a laser beam is so scattered that it can only be seen along a distance of 1 cm, the tracks branch out to a great degree and have broad crowns, like trees, consisting of very thin whiskers.

(9) In films absorbing laser light (for instance, containing dyes), whose bulk solutions absorb a beam at a distance of about 1 cm, laser tracks have their usual shape, and as such a film gets older and thinner, narrow whiskers propagate in it at distances 5 – 10 times greater than in the bulk of the same solution.

(10) The wavelength of the light exiting the whiskers coincides, with an accuracy up to 0.001 nm, with the wavelength of the input laser.

(11) Like separate small light beams, the whiskers quickly (with no delay) follow the input beam, changing each time it changes its position and direction. The time of their formation does not exceed 10 ns.

In the discussion of possible mechanisms for the observed behavior of laser tracks, many hypotheses have been proposed. The list of possible reasons includes the usual self-focusing, formation of photonic crystals and coating layers around the whiskers due to the hyper-sound excitation, reorientation of molecules, transverse reorganization of the film and formation of optical spatial solitons, peculiarities of the light field quantization in thin films, track visualization of cosmic particles, long inhomogeneous threads existing in the films, sound ripples, thermal effects, and so on. However, none of these mechanisms provides a comprehensive explanation for all the observed features in the behavior of the whiskers.

In this case the self-focusing hypothesis is not convincing since the observed narrowing of the whiskers is independent of the pump power, which in our experiments varied by nine orders of magnitude. Such behavior is not typical for any known mechanism of self-focusing. Formation of photonic crystals due to a hyper-sound coating around a whisker cannot occur because of considerable damping of hypersonic waves at such frequencies. A noticeable reorganization of molecules in the whiskers, similarly to the case of optical tweezers, would require much higher intensities and would lead to the interaction and mutual influence between the whiskers at their crossings, while no interaction is observed in experiments. Thermal effects do not apply here, since absorbing agents added to the solution do not change the behavior of the whiskers. Any new properties of angular and spatial quantization of light in thin films would depend on the film thickness but the whiskers sometimes do not feel the thickness of the film and propagate along straight lines in films of different colors [6]. Formation of solitons usually requires higher intensities and higher nonlinearities, which have not been observed for soap films. The film does not contain any long inhomogeneous light-guiding threads. One could comment on the other proposed ideas as well, but none of them is able to explain how the linear properties of the medium can provide nonlinear transformation of light into thin whiskers with sharp ends.

Behavior of light in thin films was theoretically studied, for instance, in monograph [8], with the analysis of all possible vibration types (waveguide modes), but the tendency of light to form narrow streamers was never mentioned there. At the same time, the observed differences between the refractive indices for different whiskers coming from a single focal zone can be well explained in terms of their mode structure if we assume that each whisker is a separate light mode of the film.

The mode structure of observed radiation can also be used to explain the behavior of the whiskers that have been already formed. Putting aside the question about their formation dynamics, we can easily explain the operation of a formed channel in terms of light interference with re-emission. Each part of the film bounded by monolayers of oriented polar soap molecules becomes, upon the incidence of a tangent or grazing light beam, a secondary source, an oscillator, which re-emits the same surface light waves in all directions. This occurs according to the Huygens – Kirchhoff principle but for some reason is not accompanied by the usual divergence of the channel following from this principle. Excited areas placed along the same whisker operate as a directed linear traveling-wave antenna, well known in microwave (MW) physics and dealing with surface electromagnetic waves (see, e.g., [9, p. 384]). In such antennas, excitation propagates through the leading dielectric rod along a radiating system of oscillators from one end to the other, and this is why they are called 'series-fed antennas' (Fig. 18). Such an antenna radiating in the axial direction can be viewed as a continuous set of transverse emitters. A single whisker is a linear system of oscillators, which is for some reason selected in the homogeneous medium. Being pumped by the laser, the system performs in-phase emission along the whisker axis. Similarly to a linear directive series-fed antenna, a whisker,

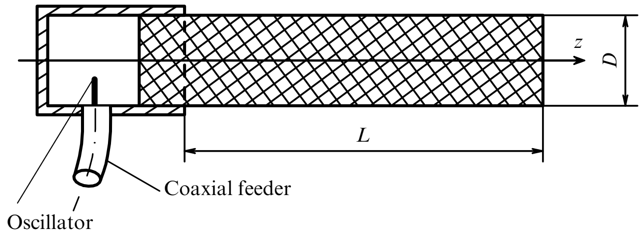

Figure 18. Scheme of a directed traveling-wave series-fed microwave antenna with axial emission [7].

depending on the phase conditions, has the divergence (the full width $\Delta\theta$ of the central lobe in degrees at half maximum power) [9]

$$\Delta\theta = (107^\circ - 61^\circ)\left(\frac{\lambda}{L}\right)^{0.5} . \tag{1}$$

If the typical whisker length L is about several centimeters and the wavelength $\lambda \sim 0.5$ μm, the directivity grows with the increase in length and is on the order of $10^{-2} - 10^{-3}$. Similarly to the case of antennas, radiation in a film is coupled with the medium by means of a surface wave. Clearly, the operation of whisker antennas does not depend on the sort of soap, the film thickness (provided that the film is thinner than 10 μm, i.e., supports surface waves), temperature, or pump power. The whiskers arise (see Section 5) and become self-organized at the inhomogeneities near the focal point by virtue of different modes. They rapidly grow and can cross without interaction since each one is fed by its own linear sources. Refractive indices for tracks in nanometer films are, according to our observations, almost as small as unity. This can be explained (similarly to the case of a microwave antenna with a rod thickness comparable to the wavelength) by the fact that most of the power is transmitted through the air near the tracks, while the phase velocity, which is then determined by the external medium, is close to the speed of light. For the most efficient microwave antennas of this kind, the thickness typically should be about $0.5 - 0.3\lambda$. For light, this makes $0.3 - 0.15$ μm, which is in good agreement with the usual thickness of our films. Various types of light oscillations (modes) excited in the focal area and seen from above as tracks with various dash lengths have different coupling with the film and hence their refractive index values are also different. Therefore, in the case of an input beam incident at a grazing angle, separate whiskers are formed, each one having its own direction. The number of whiskers formed in the medium is limited by the number of modes, i.e., oscillation types for surface waves in the film [8]. The threshold ratio of the film thickness t to the light wavelength λ for the propagation of transverse electric (TE) and magnetic (TM) modes of the order m is, in the case of a symmetric planar waveguide,

$$\frac{t}{\lambda} = \frac{m}{2(n_2^2 - n_1^2)^{0.5}} , \tag{2}$$

where n_1 is the refractive index for the medium surrounding the film (air) and n_2 is the refractive index of the film [8]. According to this estimate, a film of thickness $2 - 2.5$ μm can support modes with m up to 7. As to the principal mode with $m = 0$, it can propagate along a film, with any (even extremely small) thickness. It was shown in Ref. [8] that for the principal mode, the refractive index is the largest and usually approaches n_2. Higher-order modes have refractive indices closer to n_1, which is in agreement with our observations when several whiskers emerge from the focal point. The modes are orthogonal to each other [8], and this explains the absence of interaction between the crossing whiskers. The origin of several tracks emerging in films of thickness less than 0.15 μm will be considered in Section 5.

Large optical inhomogeneities cause bending of the whiskers and sometimes their splitting into more narrow antennas. There are particularly many branches observed in a convex film. If the input laser beam is focused onto such a film orthogonally to its border (see, for instance, Fig. 1), then a single track emerges after the focal point, but this track includes a set of surface modes propagating along a single channel. As they meet inhomogeneities or thickness variations, the modes split, due to the considerable spread between the refractive indices for different vibration types, forming branches of the main track. For a convex film, the thickness is reduced near the center and, therefore, not every track reaches the center. Sometimes, a track with the branches split away contains a single well-resolved mode with clearly seen long dashes. The thicker the film, the more modes in a track and the more branching it shows.

In experiments with absorbing films, as we already mentioned in Ref. [4], reduction of the film thickness leads to a considerable increase in the path length of the whiskers. Clearly, in a thin film the coupling of surface radiation waves with the medium is small (the energy propagates along the air, as in an antenna [9, 10]). For this reason, light in a thin film track propagates distances ten times longer than in the bulk of the solution.

Thus, what we observe in the films (as in distributed resonators) is linear wave behavior and interference of light. In contrast to the microwave case, where directed dielectric traveling-wave microwave antennas usually operate in the frequency range between 2 and 10 GHz [7], soap films provide the propagation of surface waves in a new medium at light frequencies. They are excited by a directed coherent laser beam. For the radiation of a microwave antenna, the direction is determined by the rod, while in a film, the channels are formed by themselves. With a weak laser beam (632.8 nm, 5 mW) hitting the rim of the film, we managed to obtain whiskers even without focusing the beam. The length of a microwave antenna, as a rule, does not exceed 10λ; at the same time, linear 'whisker antennas' excited by a laser beam in a thin film can provide in-phase forward emission of radiation, with the lengths of 'whisker antennas' of the order of tens of centimeters. The whiskers can have lengths of $(10^4-10^6)\lambda$ and operate both in the emitting and receiving regimes. Microwave antennas operate within a narrow frequency range, ten to a hundred times smaller than the central frequency, while the operation interval of the films is determined by their transparency range and covers a broad spectrum corresponding to visible and infrared light.

Any optical inhomogeneities in the film that influence the propagation of light will change the directions of the tracks and hence the tracks can be used as highly sensitive detectors. Using electro-optic media and standard externally controlled or mode-converting optical systems, one can provide fast switching of the whiskers and create address-controlled non-interacting waveguides. As an example, we managed to change the direction of the whiskers in a very simple way, by means of a local shock wave from a small electric discharge above the film.

A theory remains to be developed that could explain the behavior of 'whisker antennas' in thin films. It is important to find out which media are most efficient for observing this phenomenon, what the optimal conditions for the excitation of the whiskers are, and how to provide the radiation output. Thin films can also act like amplifying laser media [4, 5]. We have discovered that the films where we observed the whiskers can be used, at higher concentrations of dye molecules, as lasing media. With intense pumping (532 nm, 10 ns), tunable laser emission can be obtained in such films, similarly to the way it is obtained in dye lasers. In this case the film was immediately torn as a result of the laser pumping, and no whiskers were discerned in the emitted light [4]. This example of antenna-track formation of narrow beams can also be useful for the study of oscillation phenomena in other fields of physics.

Thus, the behavior of the whiskers after their formation can be explained in terms of the known properties of microwave antennas [9 – 11] and light propagation in thin films [8]. This explanation provides the answers to some questions posed in Ref. [4] and suggests future experimental and theoretical investigations of controlled waveguide antenna devices in optics with selective mode excitation [9, 11], including optical computers.

Thus, the tracks in a film are definitely related to its modes. Still, one question remains unsolved: how are these tracks formed in a homogeneous two-dimensional medium?

5. On the nonlinear mechanism of track formation

The results presented above demonstrate that a track fed by a single radiation mode can work as a light antenna. But what is the mechanism of such narrow track formation in a broad film? What is the mechanism underlying the selection of a single light streamer in the film? There are at least four reasons for the completely different behavior of light, namely, spreading instead of following a narrow channel:

(i) a light channel with a thickness on the order of micrometers (5 – 30 μm) should have diffraction divergence; (ii) in an opaque soap solution, light should scatter; (iii) inhomogeneities of the film surface covered by capillary waves, which make the tracks more bright and visible from above, should also cause the scattering of energy; (iv) in a homogeneous film, light should diverge after the focal point, since the input laser beam has an aperture focusing angle of about 0.02.

Each of these reasons is sufficient for expanding a laser track up to at least several millimeters at a length of 30 cm. However, one can see in Fig. 19 that a track induced by a focused CW semiconductor laser pointer (5 mW) in a concave liquid film and going along a complicated multi-loop trajectory with a total length exceeding 30 cm has no divergence of this kind, although all the above factors are

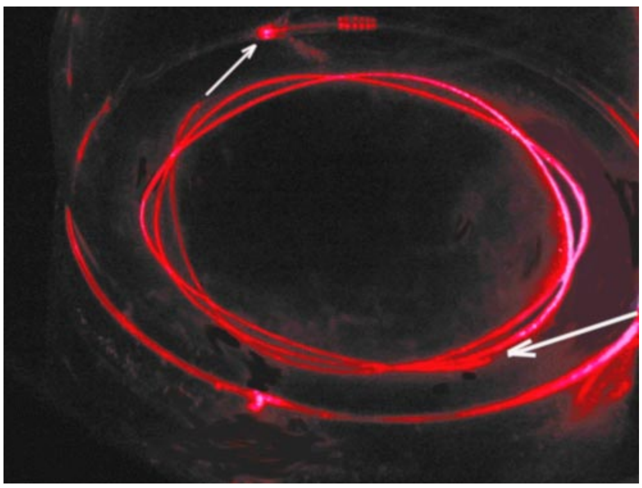

Figure 19. A three-loop track in a concave liquid film with diameter 65 mm. The total length of the track is 35 cm. The focal point of the laser beam and the exit point of the light are shown by arrows.

present. A homogeneous film cannot support a narrow waveguide mode like the one of the track unless there exists some dielectric structure guiding the light.

The unusual behavior and properties of the laser channels are definitely related to the *nonlinearity* of the film medium containing the soap molecules. This nonlinearity manifests itself not only in the narrow shape of the tracks but also in the other properties that we have already mentioned:

1. Grazing incidence of laser radiation on the film from the air creates the whiskers. (According to the classical viewpoint, light entering a film at a grazing angle should leave it quickly, after only several reflections, without forming long tracks with almost total internal reflection.)

2. In a pre-black (silvery) film, which is less than 100–150 nm thick, instead of a single track (a single principal mode), as one should expect according to the classical formula (2) at $n_2 = 1.5$, a set of 3 to 7 narrow tracks emerges. The tracks follow some fixed paths, each one corresponding to its own refractive index.

3. Along the whole length of a track, a noticeable dashed structure is formed. This structure is not at all typical for a classical principal mode propagating in a thin layer.

4. A beam entering a round concave film keeps going along the chords, with total internal reflection, i.e., the medium lets the light in but does not let it out.

The existence of narrow non-divergent waveguide channels unambiguously indicates that the local refractive index n_2 of the medium increases in the tracks due to the influence of laser radiation, even if the radiation is weak. The additional increase in the refractive index can be estimated from the following considerations. For tracks to be formed, a laser beam should be fed into the film at a known grazing angle ($\approx 5°$). Then the refractive index inside the beam is slightly increased (from n_2 to $n_2 + \Delta$), so that further, the beam propagates in the film with total internal reflection. Estimations show that Δ / n_2 does not exceed 1%.

For a track width of 30 μm and a refractive index difference between the track and the surrounding film of 1%, from Eqn (2) with $t = 30$ μm we obtain that even in a film of thickness 150 nm, such a self-organized waveguide channel can support about seven modes. Since Δ is small, and since the channels are fed by different modes, they do not 'notice' each other, and any interaction between them can be expected only at angles of intersection smaller than 1°.

As light propagates along the thin channels (waveguide antennas), the tracks grow longer since they increase the refractive index near their ends. After the light is turned off, the channels disappear. Light transforms the medium, and the medium collects the light. There are several ways of such cross-influence [12, 13] but the phenomenon we are discussing here has an important distinguishing feature. According to our estimations, the phenomenon is related not to the intensity of light, which is quite small for some of our experiments (30–1000 W cm^{-1}), but rather to the *large gradients* of the light intensity in the film and the dielectrophoresis of molecules resulting from it.

Dielectrophoresis, or the motion of particles in an electric field, takes place whenever there is a DC or AC electric field with a gradient or inhomogeneity. This effect has been known for as long as 2500 years [14] and can be easily observed when small pieces of paper are attracted to an electrified dielectric stick. The inhomogeneity of an electric field creates a force acting on any polarizable object, charged or non-charged. Under the influence of such a field, whose value can be different at various points of a particle, the particle will be drawn into the area of the stronger field if its polarizability at a given frequency is larger than that of the surrounding medium (positive dielectrophoresis). At the same time, a particle with a polarizability lower than that of the surrounding medium will be pushed out from the area of the stronger field (negative dielectrophoresis). The force of this action is determined by the gradient of the time-average field squared and does not depend on the field direction. The largest gradients arise near electrodes with very small, nanometer-scale, curvature radii [14–17] but such electrodes are very hard to manufacture.

In our case, the gradients necessary for the molecules and particles of the solution to be oriented and moved via dielectrophoresis are created by themselves, more specifically, due to the laser radiation focused onto the film, between the sharp (angstrom-thick) ends of densely packed soap molecules of the two mono-molecular surface layers [18]. This 'laser dielectrophoresis' leads to the re-orientation and shift of molecules and particles in the solution, to their cross-influence, to dipole-induced attraction, and to the formation of growing chains [17]. Altogether, this results in the growth of the refractive index and the creation of thin light channels in the film. Laser dielectrophoresis [18] seems interesting from the viewpoint of nanotechnologies and can also be employed for the selective separation of nanoparticles and molecules. In the future, it is planned to study the dynamics of dielectrophoresis. In particular, it is interesting to clarify whether new hydrogen bonds appear between the molecules in the track and whether, for instance, the freezing temperature of the solution changes in the track.

The above-mentioned increase in the refractive index, which apparently takes place in the observed phenomenon, allows one to draw a general conclusion about the origin of laser tracks. Surface light waves that propagate in flat or bent films along narrow non-divergent tracks are related to the reorganization of the medium and to the stimulated changes in its polarization properties. Therefore, they are excitations of combined electromagnetic and polarization energy, and can be classified as a special type of surface polariton soliton, which was described in Ref. [3] without specifying its origin, and which can be formed at very small light intensities. The existence of whiskers demonstrates that weak light can influence the properties of a transparent medium by changing its atomic and molecular structure.

From the practical and methodological viewpoint, it is important that since narrow laser tracks in a soap film can be easily observed (e.g., by means of a semiconductor laser pointer), the highly scientific field of nonlinear optics becomes visual and accessible for all people (schoolchildren in particular [19]) or, figuratively speaking, becomes the public property.

6. Conclusion

Behind the presented qualitative picture of the behavior of whiskers, there is the rather complicated problem of their theoretical description. The above-suggested mechanism of track formation requires further development. It is necessary to find the limits of its applicability and the optimal conditions for its manifestation. In the future, it is planned to master the technique of switching and control of the light channels, and to find their energy and information capacity. In this connection, it is interesting to study the propagation of

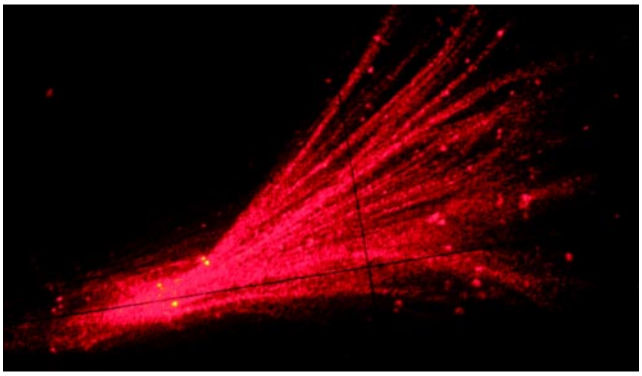

Figure 20. Tracks in a free dry film of dammar varnish, with a thickness of about 1 μm, under the microscope.

broadband femtosecond 'bullets' along the laser tracks.

The discovered phenomenon of self-compression, i.e., transformation of a weak laser beam into self-sustaining thin tracks, is directly related to the interaction between laser light and nano-objects. It is important to understand the reorganization of molecules in the liquid inside a track, as well as the role of the residual liquid and the mobility of molecules in rigid but highly hygroscopic soap films. It is also interesting why somewhat similar laser tracks can be observed under the microscope not only in soap films but also in a thin free-standing film (Fig. 20) obtained from a small drop of dammar varnish. The drop was spread on the surface of water, so that its diameter became about 6 cm, hardened in the shape of a very thin film, and was then lifted from the water into the air using a frame. From the interference fringes seen in the reflected light we could conclude that the thickness of the film did not exceed 1 μm. It should be also mentioned that no laser channels were observed in thick liquid films of honey or albumen aqueous solution. Previously we investigated [20] film ispalators with turbulent fluxes and also observed laser channels but in that case the channels were not so narrow as in still soap films.

The observed laser tracks provide valuable information about the structure and properties of both the films and the nanoparticles in these films. Therefore, tracks can be used for the study of these structures. There is an interesting analogy, probably a very profound one — the tracks look like the trajectories of an electron beam moving between point-like scattering centers in a thin film [21], which are not observable but can be calculated theoretically. Soap films also contain scattering centers, which change the directions of laser tracks, and it would be interesting to control the properties of these centers. Much interest is attracted to the study of the tracks and their laser properties in soap films of various thickness [22, 23], which have been investigated for quite a long time, or in biological membranes, which are the basis of all living matter. Let us stress once again that a film with whiskers is in fact a continuously working high-power optical computer with a giant parallel processor. It guides a thin laser track through millions of its cells, so that both the direction of the track and the properties of the computer change under the influence of the laser light and the external conditions.

For reasons we consider evident [24 – 26], our efforts in developing these studies and attracting attention to this phenomenon have had little success so far. Still, we hope that our finding, which originated from pure curiosity and sincere interest, will be useful some time. "A common path to it will not be ever lost", other researchers will follow the path, and our results will form the basis for many directions of future studies. We are grateful to our friends for their support, discussions, lasers they lent to us, samples of shampoos and pure surface-active agents, and the solutions for making rigid films.

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